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**ON THE GENESIS OF RING FRACTURES
OF THE BASE OF THE SKULL AND
FRACTURES OF THE VERTEBRAL COLUMN,
ESPECIALLY OF ATLAS AND AXIS**

Lund 1978



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This dissertation is based on the following publications:

- I. Voigt, G.E. and Sköld, G.: Ring fractures of the base of the skull. J. Trauma 14, 494-505, (1974).
- II. Sköld, G.: Fractures of the arches of the atlas: A study of their causation. To be published.
- III. Sköld, G.: Fractures of the neural arch and odontoid process of the axis: A study of their causation. To be published.
- IV. Sköld, G.: Fractures of the axis caused by hanging. Z. Rechts-med. 80, 329-331, (1978).
- V. Sköld, G.: Sagittal fractures of the cervical spine. Injury (in press), (1977).
- VI. Voigt, G.E., Löwenhielm, C.G.P. and Sköld, G.: Experimental atlas and axis fractures - A pilot study. To be published.
- VII. Sköld, G. and Voigt, G.E.: Spinal injuries in belt-wearing car occupants killed by head-on collisions. Injury 9, 151-161, (1977).

In the text these papers will be referred to by their Roman numerals.

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INTRODUCTION

Accidents, mostly traffic accidents, every year take a great toll of human lives, while a still greater number of persons are injured. Great efforts have been made (1) to diminish the number of accidents by mainly technical measures and education and (2) to decrease the effect of accidents with respect to bodily injuries by protective measures. For the last-mentioned purpose knowledge of the genesis of the injuries is essential.

Blunt trauma can cause injuries either directly, i.e. at the site of impact, or indirectly, i.e. away from the impacted area. Impact energy can be transferred through the body. The injurious effect depends on the strain-stress capability of the tissues involved. Concerning the head-neck junction, ring fractures of the base of the skull and most fractures of the atlas and axis are typical indirectly-caused injuries often found in accident victims sustaining blunt trauma to the head.

For centuries cervical spine injuries have been feared because of their frequent association with injuries to the central nervous system. A clinical description was recorded in the Edwin Smith papyrus (Power, 1934) by a medical author who wrote in 2500 B.C.: "One having a crushed vertebra of his neck; he is unconscious of his two arms and his two legs and he is speechless. An ailment not to be treated". The central nervous system injuries associated with fractures of the upper part of the cervical spine (and/or base of the skull) are not seldom immediately fatal. It is, therefore, not surprising that fractures of the cervico-cranial junction have been studied for many years. An extensive survey of ring fractures of the base of the skull was published already in 1934 by Le Count et al. As early as 1920 Jefferson presented his classical theories concerning

the genesis of atlas fractures. Concerning bilateral fractures of the neural arch of the axis Wood-Jones in 1913 coined the expression "the ideal lesion produced by judicial hanging". In 1965 Schneider et al pointed out that this injury is occasionally found in traffic accident victims and termed it "hangman's fracture" of the cervical spine. As early as 1928 Osgood and Lund made a survey of fractures of the odontoid process of the axis.

Many studies concerning the genesis of fractures of the arches of the atlas and of fractures of the odontoid process or neural arch of the axis are based on clinical material. However, it is well known that X-ray cannot fully demonstrate fractures and soft tissue injuries in the neck. Voigt (1968) emphasized that the shape of the fracture surfaces and the soft tissue injuries around the fracture(s) often allow movements of the fracture fragments only in the same way as occurred when the fractures arose. Hinz (1972) pointed out that the localization of injuries to the intervertebral discs and ruptures of the longitudinal ligaments are informative in evaluating the deformation of the cervical spine resulting in fractures. It has also been shown (Voigt, 1969) that further knowledge about the deformation of the victims body causing the fractures can be gained by careful reconstruction of the course of events in the accidents by correlating the victims' external injuries to the findings at the scene of the accident. Such a close reconstruction has usually not been performed in the available publications concerning the indirectly-caused fractures of the cervico-cranial junction.

The above-mentioned statements concerning the earlier studies of fractures of the cervico-cranial junction are valid also for the rare sagittal fractures of the cervical vertebral bodies.

The protective effect of seat belts to car occupants is well-known. Nevertheless, it has been claimed that the risk of injuries to the neck (whip-lash) may be increased by the use of shoulder or combined lap-shoulder belts. Therefore, a close investigation of the cervical spine in such accident victims is felt to be essential.

The purpose of the present investigation is to contribute further to the knowledge of the genesis (but not the frequency) of:

1. Ring fractures of the base of the skull.
2. Fractures of the arches of the atlas.
3. Fractures of the odontoid process or neural arch of the axis.
4. Sagittal fractures of the cervical vertebral bodies.
5. Cervical spine injuries in belt-wearing car occupants sustaining head-on collisions.

The method used is a correlation of:

1. The shape of the fracture surfaces.
2. The injuries to the soft tissues near the fracture(s).
3. The results of reconstruction of the course of events in the accident.

In addition, a short experimental study has been performed to verify the interpretations of the findings in the main investigation based on autopsy material concerning fractures of the atlas and axis.

METHODOLOGICAL CONSIDERATIONS

The presence of a ring fracture of the base of the skull, except for the very special type of marginal fracture at the anterior border of the foramen magnum, is obvious at autopsy. In order to determine the mode of origin of the fracture it is important that a possible abnormal mobility of the head is established both before and after the skull is opened. The site of a possible lesion of the dura mater can also aid in the interpretations. When manipulation of the head does not suffice to establish the type of fracture (traction or torsion type) the localization of the essential impact is of decisive importance.

For the investigation of the cervical spine the posterior part of the base of the skull, the cervical spine including the surrounding soft tissues, the medulla oblongata and the cervical spinal cord have been removed en bloc in this study. In the beginning of the study the specimens were bisected after freezing in the sagittal plane in the midline to demonstrate injuries to the intervertebral discs and the longitudinal ligaments. In earlier similar investigations (Hinz, 1970) the cervical spine has usually been cut sagittally also through the apophyseal joints. The experiences from the investigation of some cervical spines prepared in this way revealed that incomplete fractures of the apophyseal joints (which are often very informative in the determination of the deformation of the spine in the accident) can be impossible to demonstrate and that abnormal mobility of the spine (after thawing) due to injuries to the soft tissues is difficult to determine. However, it was established - especially concerning fractures of the atlas and axis - that it was sometimes easier to determine the deformation of the cervical spine which caused the fracture(s) if the movement testing and the soft tissue preparation were performed without previous bisecting in the sagittal plane in the midline.

The maceration of the specimens was performed in warm tap water (60°C) for 2-3 days. This allowed easy removal of the soft tissues and the fractures could be fully demonstrated.

The investigation of the scene of the accident was usually done by the same person who performed the autopsy. Damage to the cars involved in the accidents was often very informative in analyzing the genesis of the injuries to the occupants. The second collision, i.e. the impact of the occupant against the interior of the car, was in most cases easily reconstructed with the help of a dummy. The external injuries of the body of the victim were indicated on the dummy (the size of which could be adjusted to the size of the victim). By placing the dummy in the wrecked vehicle, the injuries could easily be correlated to the car damage, i.e. to steering wheel, dashboard, windshield etc. in most cases. Blood stains, skin and hair fragments found on the vehicle indicated contact points as well as flakes of varnish and glass splinters in the victims' wounds. These correlation measures usually allowed reconstruction of the direction of the impact and of the pattern of movement of the different parts of the victim's body.

SUMMARIES OF THE PAPERS

Ring fractures of the base of the skull (I)

It has hitherto been considered that complete or incomplete ring fractures of the base of the skull are due to impression of the vertebral column into the interior of the skull (trauma against the vertex of the head or the feet-buttocks), to traction (hyperextension, retroflexion) of the head-neck (trauma against the face from anteriorly and inferiorly) or to anteroflexion-traction of the head-neck (trauma against the occiput from posteriorly and inferiorly).

In the present investigation, based on 77 cases with ring fractures of the base of the skull, there were several cases in which the fracture had arisen through the above-mentioned, earlier known mechanisms. However, it was found that ring fractures running in the floor of the middle fossae and through the squama of the temporal and occipital bones (the classical type) can be due to several mechanisms not earlier suggested.

1. Torsion in the base of the skull by trauma obliquely from in front against the temple or obliquely from behind against the posterior part of the side of the head. This was the most common type of ring fracture of the base of the skull in this material.
2. Wedge effect due to a blow against the forehead leading to a deformation of the base of the skull by increasing its transverse diameter at the level of the anterior fossa.
3. Retroflexion of the head due to trauma against the occiput directed below the center of gravity of the head.
4. Anteroflexion of the head due to a blow from above and behind against the posterior part of the vertex of the head. In such cases the anterior part of the base of the skull is forced in an inferior direction.

It is thus evident from this investigation that quite different traumata can cause ring fractures of the base of the skull of roughly the same shape. This is probably due to the anatomy of the base of the skull. The shape of the incomplete ring fractures indicates that the fractures (apart from those due to trauma against the occiput from behind and below) start in the floor of the middle fossae, an area which owing to foramina, sutures, fissures, and canals in the bone is weak (foramen lacerum, sutura sphenotemporale, fissura petrosquimalis, canalis caroticus and acusticus meatus), and continue into the squama of the temporal and occipital bone.

It was also found that a trauma from below and from in front against the face can cause not only the above-mentioned, classical ring fracture but also expulsion of the corpus ossis occipitale and marginal fracture at the front side of the foramen magnum. Thus, the same type of trauma can result in ring fractures of the base of the skull of quite different appearances.

The present investigation also includes one case in which the victim, who wore a helmet, sustained an exceptionally strong blow against his face from in front. The entire body of the occipitale bone, together with the surroundings of the foramen magnum had been expelled. The shape of the fracture surfaces and the injuries to the surrounding soft tissues indicate that this ring fracture was due to displacement of the periferal part of the base of the skull in a posterior direction in relation to the central part (shearing effect).

Fractures of the arches of the atlas: a study of their causation (II)

A well-known and generally accepted theory concerning the genesis of atlas fractures is that axial compression of the cervical spine creates a wedge effect, i.e. compression of the atlas between the skull and the axis causes dislocation of its lateral masses in lateral direction due to the inclination of the joint surfaces towards the occipitale condyles and towards the superior

joints of the axis.

In contrast, in the present material in all 7 cases sustaining fractures of the atlas due to trauma to the vertex of the head or feet-buttocks the findings, because the compression of the upper part of the neck did not take place in a straight superior-inferior direction, indicate that other mechanisms caused the atlas fractures.

Thus, in 4 cases compression of the neck was combined with oblique retroflexion of the head resulting in dislocation and tilting of the lateral mass of the atlas on the most affected side in posterior direction. This movement caused strains and stresses in the anterior arch between the lateral mass on the most affected side and the part of the arch supported by the odontoid process of the axis. Fractures of the posterior arch observed in 3 of these cases, obviously are due to its impact against the neural arch of the axis during the dislocation and tilting of the lateral mass. In the remaining 3 cases the compression of the upper part of the neck was most pronounced anteriorly and somewhat laterally. Under those circumstances the anterior margin of the superior joint surface of the axis on the most affected side acted like a wedge splitting off and dislocating the anterior side of the atlas from below. Fractures in the posterior arch observed in 2 of these cases may be ascribed to torsional strains because of dislocation of one lateral mass in inferior direction in relation to the other, to impact from a separated neural arch of the axis or to wedge effect after the stability of the atlas ring has been lost.

That trauma against the chin from anteriorly-inferiorly can cause fractures of the posterior arch of the atlas due to a crush between the occipital bone and neural arch of the axis during retroflexion (hyperextension) of the head is another generally accepted opinion.

In the present material there are 6 cases with fractures of the atlas due to trauma against the victims' chins from in front and below.

In 3 of these 6 cases there were simultaneous bilateral notably non-symmetrical fractures of the neural arch of the axis probably caused by oblique anteroflexion of the head in combination with traction of the neck, while no cases showed fractures of the atlas simultaneously with almost symmet-

rical bilateral fractures of the neural arch of the axis. In another 2 of the 6 cases there were other findings (avulsion of the right occipital condyle, a notably obliquely running fracture in the posterior arch of the atlas) indicating traction of the neck most pronounced on either the right or left side. Thus, our findings indicate that non-symmetrical traction of the neck causes considerable strains and stresses in the atlas, reasonably because of non-symmetrical tension in the ligaments in the upper part of the neck. However, the details are not yet known.

The sixth case displayed fractures in the grooves for the vertebral arteries reasonably due to retroflexion of the head combined with only slight traction of the neck.

In the present material all 4 cases displaying bilateral fractures of the posterior arch of the atlas due to trauma against the forehead from anteriorly-superiorly also exhibited tilting-dislocation in posterior direction of the fractured odontoid process of the axis. Obviously, due to the fixation of the anterior arch to the odontoid process, this movement of the odontoid process caused the posterior arch to be pressed against the neural arch of the axis and bending fractures easily arose. Fractures of the anterior arch in one of these cases may have been due to wedge effect after the stability of the atlas ring had been lost or to dislocation-tilting in posterior direction of one lateral mass of the atlas because of the retroflexion of the head taking place in a somewhat oblique direction.

Although avulsion fractures of the inferior margin of the anterior arch of the atlas are considered very rare lesions, 5 cases were seen in the present material. The findings support the suggestion that these fractures are caused by traction of the muscles and ligaments inserting at the anterior arch, but also indicate that lateral tilting of the head is essential in their genesis.

Fractures of the neural arch and odontoid process of the axis: A study of their causation (III)

Bilateral fractures of the anterior part of the neural arch of the axis (hangman's fracture) are often seen in traffic accident victims. The general opinion is that such fractures are due to retroflexion of the head. In contrast, in all 20 cases in the material presented here the findings indicate that the fractures were probably due to anteroflexion of the head.

In 12 cases the anteroflexion of the head was due to the inertia of the head after impact against the lower part of the face, in one case after impact against the anterior side of the neck. The result of the reconstructions indicates that in all 13 cases the trauma was directed not only from in front but also from below, i.e. a simultaneous traction of the neck of considerable degree occurred. The ultimate importance of the traction in the development of the fractures is not known but it is possible that it inhibits the participation of the middle and lower cervical spine in the anteroflexion of the head, increasing the strains and stresses in the upper part of the neck. In 3 cases the anteroflexion of the head was obviously combined with compression of the neck, due to trauma against the posterior part of the vertex of the head from posteriorly-superiorly and in one case due to trauma against the feet. Besides traction, compression may inhibit the participation of the middle and lower cervical spine in the anteroflexion of the head. Notably non-symmetrical fractures of the neural arch seem to be rare. The findings indicate that they arise due to anteroflexion of the head, however, in oblique direction, in combination with traction of the neck. Bilateral fractures of the neural arch posterior to the inferior apophyseal joints seem to be very rare. In one observed case the cause may have been impact against the posterior part of the neck, possibly in combination with anteroflexion of the head.

In 17 cases in this material anteroflexion of the head caused fractures of the odontoid process of the axis. In 4 cases the anteroflexion was due to trauma against the posterior part of the vertex of the head from posteriorly-superiorly (causing also compression of the neck) and somewhat from

the lateral side (causing also rotation of the head) and in one case to trauma against the posterior part of the head while the anterior side of the neck was decelerated. In 12 cases the anteroflexion was due to the inertia of the head after impact against the lower part of the face. The result of the reconstructions in all 17 cases indicate none or only slight simultaneous traction of the neck.

In 6 cases in this material retroflexion of the head caused fractures of the odontoid process of the axis. The trauma was directed against the forehead from superiorly-anteriorly resulting in a simultaneous compression of the neck. The presence of bending fractures of the posterior arch of the atlas in 3 of the cases indicate that the retroflexion of the head and not shearing effect in the horizontal plane via the anterior arch of the atlas was of utmost importance in the genesis of the fractures of the odontoid process.

Thus, in all cases with fractures of the odontoid process of the axis due to trauma against the forehead or to the posterior part of the head (except the one sustaining impact against the anterior side of the neck) the findings indicate a simultaneous compression of the neck. As in the cases showing fractures of the neural arch, it seems possible that this compression is of importance by inhibiting the movements of the middle and lower part of the cervical spine and thus increases stresses and strains in its upper part.

Obviously, trauma against the lower part of the face causing anteroflexion of the head due to its inertia can result in fractures either of the odontoid process or the neural arch of the axis. The findings indicate that a considerable degree of simultaneous traction in the neck promotes the localization of the fracture to the neural arch. Also trauma against the posterior part of the vertex of the head from posteriorly-superiorly can cause fractures either of the odontoid process or the neural arch of the axis. The findings indicate that simultaneous rotation of the head promotes the localization of the fracture to the odontoid process.

In this investigation no correlation could be found between the level of the fracture of the odontoid process and the type of trauma. A remaining cartilaginous disc in the body of the axis however, may be of importance in the shape of the fracture.

Fractures of the axis caused by hanging (IV)

According to general opinion prerequisites for bilateral fractures of the anterior part of the neural arch of the axis (hangman's fracture) in judicial hanging are a considerable drop (causing traction of the neck) and a submental knot (causing retroflexion of the head).

In a case of suicide by hanging the drop was 2-3 meters and the noose of the line was located behind the victim's left ear. The axis showed a fracture running through the posterior part of the left superior joint surface and the foramen transversarium, an incomplete fracture running from the posterior part of the right superior joint surface in an inferior direction, and a fracture in the right half of the neural arch running from the inferior joint surface postero-superiorly with a small incomplete fracture running from this fracture in an anterior direction on the lateral surface of the neural arch. Due to the shape of the fracture surfaces and laceration of mainly the posterior part of the intervertebral disc between the axis and C 3, tearing of the ligamentum flavum and the posterior longitudinal ligament between the axis and C 3 and avulsion of the anterior longitudinal ligament from the superior part of the anterior side of the body of C 3 with laceration on the left at this level the upper part of the cervical spine could be extremely anteroflexed to the right.

The anteroflexion of the head to the right evidently caused not only the fractures of the anterior part of the neural arch due to forward bending of the odontoid process and the body of the axis in relation to its neural arch, but also the torsion fractures in the right part of the neural arch due to the stretching of the neck being more pronounced on the left than on the right side.

This case demonstrates that the "classical" hangman's fracture can arise even if the knot is not located submentally and also gives considerable support to the opinions suggested in paper III concerning the bilateral fractures of the neural arch of the axis usually being due to anteroflexion of the head, the notably non-symmetrical ones to oblique anteroflexion.

Sagittal fractures of the cervical spine (V)

Sagittal fractures of the cervical vertebral bodies are considered to be rare injuries and their cause is still disputed. One theory is that due to axial compression of the cervical spine the nucleus pulposus is extruded into the cervical vertebral body, another that the compression results in a chiseling action, i.e. the sharp margin of one vertebral body splits the neighbouring body into two pieces. Two observed cases suggest another genesis.

In both cases the trauma hit the posterior part of the victim's head, anteroflexion of the head had obviously occurred and bilateral fractures of the neural arch of their axis, gaping superiorly, were present.

In one case an incomplete fracture ran sagittally in the vertebral body of C 6, gaping posteriorly. There was also a fracture of the right side of the arch and to the left of this fracture was an incomplete fracture on the anterior side of the arch. C 5 showed a fracture running sagittally through the body and a fracture of the right side of the arch.

In the other case there was a sagittal fracture of the vertebral body of C 4. Anteriorly the soft tissues, including the periosteum, were uninjured. Posterior to the fracture the periosteum was torn. There were two fractures in the arch and an incomplete fracture was found at the anterior side of the separated posterior part of the arch. Before removing the soft tissues, this part of the arch could be dislocated anteriorly with ease due to the lacerations of the surrounding soft tissues, which caused the sagittal fracture of the body to gape posteriorly.

- The anatomical findings revealed that the posterior part of the vertebral arches had been flattened before they fractured, decreasing the sagittal diameter and increasing the transverse diameter of the vertebral foramen. This evidently, gives rise to strains and stresses in a frontal plane on the posterior side of the vertebral bodies explaining the sagittal fractures running in an anterior direction. The pressure against the posterior aspects of the cervical vertebral arches may be ascribed to stretching of the ligaments and muscles of the posterior part of the neck during the anteroflexion of the head, but may also be attributed to a simultaneously occurring trauma to the posterior part of the neck.

Experimental atlas and axis fractures: A pilot study (VI)

In order to verify the opinions concerning the origination of atlas and axis fractures (II, III, IV) impact experiments with cadavers on an acceleration track resulting in fractures of the neural arch or odontoid process of the axis were analyzed and compression experiments on a separated part of human upper cervical spine were performed.

In one of the impact experiments a hangman's fracture of the axis arose due to impact against the lower part of the face. The high speed films showed that a slight anteroflexion of the head around the impact area and stretching of the neck occurred.

In another of the impact experiments a fracture of the odontoid process of the axis arose. This was ascribed to anteroflexion of the head after impact of the anterior side of the upper neck against the instrument panel and/or to impact of the face against the upper surface of the instrument panel after anteroflexion of the head.

In one of the compression experiments a hangman's fracture and compression of the inferior-posterior part of the body of the axis arose, obviously due to compression and anteroflexion of the upper cervical spine.

In another of the compression experiments bilateral fractures of the anterior and posterior arch of the atlas arose due to dislocation and tilting of one of its lateral masses posteriorly-inferiorly.

Although the results of experiments on cadaveric material are influenced by post-mortem changes of the tissues and lack of muscular tonus, the findings in this study show such similarities to the results of the investigations on atlas and axis fractures in accident victims (II, III) that they support the opinions concerning the genesis of such fractures advanced in these studies.

Spinal injuries in belt-wearing car occupants killed by head-on collisions (VII)

It is well-known that injuries to car occupants in accidents can be reduced or eliminated by the use of body-restraining seat belts. However, it has also been said that considerable strains and stresses arise in the spine in belt-wearing car occupants sustaining head-on collisions because the belts hold back part of the body while the rest of the body continues forward due to its inertia. In the present investigation the spine of 34 victims of head-on collisions have been investigated and the results correlated to the findings in the cars.

Lap-belts are incapable of preventing anteroflexion of the upper part of the body in head-on collisions.

The lower part of the face of a driver who sustained a head-on collision had struck the engine bonnet that had been bent upwards and backwards while the passenger's chin had struck the upper surface of the instrument panel. Both the victims showed bilateral fractures of the neural arch of the axis, probably the consequence of anteroflexion of the head due to its inertia after deceleration of the lower part of the face. Traction of the cervical spine may have been caused by the face being struck from below in the driver and by hyperextension of the thoracic spine in the passenger, who also had a rupture of the anterior longitudinal ligament between T 3 and

T 4 together with a tear in the front of the disc between these two vertebrae.

A shoulder belt alone cannot prevent submarining beneath the instrument panel or through an opening door.

Two cases made evident that the risk of submarining under the instrument panel of the car is considerable if the panel is placed high and/or if the occupant has short legs or if fractures cause shortening of the lower legs.

Six cases emphasised the risk of injury to the neck and/or head if the car occupant is ejected from the car, either because he was temporarily caught between jaw and neck by the belt causing extensive lacerations of the upper neck and fatal damage to the medulla oblongata-spinalis or sustained fatal injuries to the skull and brain upon hitting the ground.

In only one car occupant wearing a three-point belt did submarining take place, probably because the belts had not been correctly adjusted or because an initial impact of the car made the torso of the victim stretch the belts to such a degree that when the car later overturned, submarining was possible.

In 7 cases in which only shoulder belts were used and in 15 cases in which three-point belts were used there were no signs of submarining. All victims, however, showed injuries to the face due to impact against the car interior. In 8 cases the injuries to the face were slight (small abrasions and lacerations) and only 2 had fractures of the facial skeleton (the nasal bone). In one case there were fractures of the spinal process and inferior articular processes of C 6, fractures of the superior articular processes of C 7 and laceration of the intervertebral disc C 6-C 7; in one case, lacerations of the intervertebral discs C 5-C 6 and C 6-C 7 and fracture of the postero-inferior margin of the body of C 6 were present. Four cases showed small haemorrhages and/or lacerations of one or several intervertebral discs, while in 2 cases there were no injuries to the spine.

In the remaining 14 cases the facial injuries were severe with skin lacerations in the lower part of the face and in 10 cases also fractures of the mandible and/or maxilla. Among these 14 cases were found extensive lacerations of the soft tissue between the base of the skull and the cervical spine in 2 cases, ring fractures of the base of the skull in 4 cases, fractures of the atlas in 2 cases, fractures of the odontoid process of the axis in 4 cases and fractures of the neural arch of the axis in 2 cases.

Thus, in all 7 cases in which the injuries to the face indicated no violent impact, injuries to the cervical spine were absent or slight, not involving its upper part, while in 14 cases in which the injuries to the face indicated violent impact, severe injuries to the upper part of the neck were present in 10 cases. The present observations indicate that the belted car occupant runs no great risk of sustaining severe (or fatal) injuries to the cervical spine and/or spinal cord as long as his head does not violently strike part of the car interior and as long as no submarining takes place.

Three of the victims who had worn shoulder belts had injuries to the thoracic or lumbar spine (at the level of T 3-T 4, T 12-L 1 and L 1 respectively) and four of the victims who had worn three-point belts had such injuries (at the level of T 4-T 5, T 6, T 8-T 9 and L 1-L 2 respectively). Judged by the mainly ventrally-located soft tissue injuries they were caused by a violent extension of the middle-to-lower part of the thoracic and lumbar spine due to the inertia of the trunk while the pelvis was held down on the seat by the lap-belt and/or by the thighs and the upper part of the torso was held back by the shoulder belt. In 3 cases impact from behind (usually the unrestrained back-seat passenger) may have increased the extension.

THE ESSENTIAL FINDINGS OF THE INVESTIGATION

The experiences from the present study have yielded an informative investigation technique of the upper part of the cervical spine. In most cases a satisfactory investigation can be performed *in situ* by separating the base of the skull from the cervical spine. For this purpose the scalp at the back of the head and neck is separated from the neck muscles to the middle of the neck. The posterior neck muscles are separated from the base of the skull and the posterior atlanto-occipital membrane transected, taking care not to injure the transverse ligament of the atlas. It is important not to cut between the posterior arch of the atlas and the neural arch of the axis as the subsequent anteroflexion of the head can cause a fracture of the odontoid process of the axis. The joint capsules of the atlanto-occipital joints are transected and after dividing the remaining soft tissues between the base of the skull and the cervical spine laterally the head can be tilted anteriorly in relation to the upper part of the cervical spine. Fractures of the arches of the atlas, of the odontoid process and/or of the neural arch of the axis are then usually easily detected, especially if movement testing of the upper cervical spine is performed. For complete investigation of the neural arch of the axis, the atlas should be removed. The upper part of the cervical spinal cord (preferably together with the medulla oblongata) can be removed for microscopic investigation by cutting the spinal nerves via the foramen magnum and transecting the cord by incising through an intervertebral disc.

If an exact determination of the deformation of the head and neck causing injuries is essential, the best method is to remove the posterior part of the base of the skull together with the cervical spine including the surrounding muscles and ligaments. Determination of any abnormal mobility and of the soft tissue injuries by dissection in layers should be performed before maceration. Bisecting the preparation in the sagittal plane in the midline is recommended if injuries to the intervertebral discs and to the longitudinal ligaments are of special interest.

Correlating the results of the different parts of the present investigation gives some information concerning which indirectly-arisen fractures

of the base of the skull, the atlas and/or the axis that can be expected after impact from different directions against certain parts of the head and neck:

1. TRAUMA AGAINST THE CHIN

1.1 FROM ANTERIORLY-INFERIORLY:

Ring fractures of the base of the skull (the classical type running in the middle fossae and through the squama of the temporal and occipital bone, expulsion of the corpus ossis occipitale or marginal fracture at the frontal side of the foramen magnum) when the impact causes a considerable traction of the neck, while a simultaneous retroflexion of the head takes place. The latter is due to the direction and force of the traction exceeding the anteroflexion energy of the head due to its inertia and/or the forehead being decelerated by impact against some object.

Bilateral fractures of the posterior arch of the atlas when the retroflexion of the head is combined with only slight simultaneous traction of the neck.

Bilateral fractures of the neural arch of the axis in the region of the isthmus when the impact causes a considerable traction of the neck, while a simultaneous anteroflexion of the head due to its inertia takes place.

1.2 FROM ANTERIORLY-INFERIORLY AND FROM THE RIGHT OR LEFT SIDE:

Bilateral, notably non-symmetrical fractures of the neural arch of the axis often combined with fractures of the arches of the atlas when anteroflexion of the head takes place in oblique direction, i.e. the simultaneously occurring traction of the neck is unilaterally more pronounced.

1.3 FROM ANTERIORLY

Fracture of the odontoid process of the axis when anteroflexion of the head due to its inertia is combined with none or only slight simultaneous traction of the neck.

2. TRAUMA AGAINST THE FOREHEAD

2.1 FROM ANTERIORLY:

Ring fracture of the base of the skull (expulsion of the corpus ossis occipitale) due to shearing effect when a violent trauma due to special circumstances (helmet-wearing) does not cause only local fractures in the facial skeleton and the anterior part of the base of the skull, but also violent dislocation of the superior part of the head in posterior direction.

Ring fracture of the base of the skull running in the middle fossae and through the squama of the temporal and occipital bone due to wedge-effect when a violent trauma causes impression fractures and flattening of the forehead and thus increases the transverse diameter of the skull in the anteriorfossa of the base of the skull.

2.2 FROM ANTERIORLY-SUPERIORLY:

Fracture of the odontoid process of the axis often combined with bilateral fractures of the posterior arch of the atlas when the impact causes retroflexion (and dislocation in posterior direction, i.e. shearing effect) of the head and simultaneous compression of the neck.

2.3 FROM ANTERIORLY-INFERIORLY:

Ring fracture of the base of the skull in the same way as in 1.1 and with the same appearances.

3. TRAUMA AGAINST THE VERTEX OF THE HEAD

3.1 FROM SUPERIORLY:

Ring fracture of the base of the skull (usually comminute fractures in the floor of the posterior fossa) when the trauma dislocates the cervical spine into the interior of the skull.

Fractures of the atlas (mainly its anterior arch) when the trauma results in compression of the neck most pronounced anteriorly-laterally, causing the anterior part of one superior joint surface of the axis to act like a wedge on the anterior arch of the atlas.

Fractures of the arches of the atlas when the trauma results in compression of the neck combined with oblique retroflexion of the head. Due to this, one lateral mass of the atlas is dislocated in posterior-inferior direction, resulting in the anterior arch being pressed against the odontoid process and the posterior arch against the neural arch of the axis.

4. TRAUMA AGAINST THE POSTERIOR PART OF THE HEAD

4.1 FROM SUPERIORLY-POSTERIORLY:

Ring fracture of the base of the skull running in the middle fossae and through the squama of the temporal and occipital bone or bilateral fractures of the neural arch of the axis in the region of the isthmus when the trauma causes anteroflexion of the head and simultaneously compression of the neck. Such ring fractures may be considered a special type of 3.1.

4.2 FROM SUPERIORLY-POSTERIORLY-LATERALLY:

Fracture of the odontoid process of the axis when the trauma causes anteroflexion and probably rotation of the head and simultaneously compression of the neck.

4.3 FROM POSTERIORLY:

Ring fracture of the base of the skull running in the middle fossae and through the squama of the temporal and occipital bone when the trauma is directed below the center of gravity of the head causing retroflexion of the head.

4.4 FROM POSTERIORLY-INFERIORLY:

Ring fracture of the base of the skull running in the middle fossae and through the squama of the temporal and occipital bone when the trauma causes an impression fracture of the occipital squama elevating the calotte from behind.

5. TRAUMA AGAINST THE SIDE OF THE HEAD

5.1 STRAIGHT FROM THE SIDE:

Marginal avulsion at the inferior border of the anterior arch of the atlas when a trauma causes lateral tilting of the head, resulting in traction at the anterior arch via ligaments and muscles.

5.2 OBLIQUELY FROM THE SIDE:

Ring fracture of the base of the skull running in the middle fossae and through the temporal and occipital squama but usually somewhat non-symmetrical when a trauma against the temple or lateral-posterior part of the head causes torsional strains and stresses in the base of the skull.

6. TRAUMA AGAINST THE ANTERIOR SIDE OF THE NECK

6.1 FROM ANTERIORLY-INFERIORLY:

Bilateral fractures of the neural arch of the axis in the region of the isthmus when a trauma against the superior-anterior part of the neck (submarining, hanging) causes considerable traction of the neck, while simultaneous anteroflexion of the head takes place.

6.2 FROM ANTERIORLY:

Fracture of the odontoid process of the axis when the superior-anterior part of the neck is decelerated while the head anteroflexes.

7. TRAUMA AGAINST THE POSTERIOR SIDE OF THE NECK

Bilateral fractures of the neural arch of the axis posterior to the inferior apophyseal joints when a trauma impacts against the posterior part of the neck. However, a simultaneously occurring anteroflexion of the neck may also be of importance.

GENERAL DISCUSSION

The mechanical response of the human body to blunt trauma is complex. Not only the impact energy, the impact velocity and the direction of the trauma, but also the mechanical properties of the part of the body impacted are decisive for the severeness of the injuries arising. The solid tissue (bones) display quite different tolerance levels than the soft tissues (muscles, ligaments).

Impact against the head, where bone tissue is covered by a relatively thin layer of soft tissues leads to a rapid transfer of energy, i.e. forces of considerable magnitude and of short duration are obtained. These forces can cause not only lacerations and fractures locally but also an acceleration of the freely movable head in relation to the torso. The movement of the head gives rise to stresses of the head-neck junction and of the cervical spine with a subsequent risk for soft tissue injuries and fractures. Force levels reached in accidents cannot be sufficiently determined but a rough estimate can be obtained by the extent of the injuries and by the damage to the car. However, a good approximation of the direction of the impact to the victim's head and/or neck and the deformation of the base of the skull - cervical spine can usually be gained by thorough anatomical investigation and close reconstruction of the course of events in the accident as described above.

According to the results of this investigation there are correlations between the direction of the trauma and the localization of the impact area on the head or neck on one hand and the resulting fracture(s) of the base of the skull, the atlas and/or the axis on the other. However, it is also obvious that different types of injuries can arise in cases in which the impacted area and the direction of the trauma seem to be identical. For example, trauma against the posterior part of the vertex of the head from superiorly-posteriorly can cause either ring fractures of the base of the skull (impression fracture) or fractures of the neural arch of the axis. Trauma against the chin from anteriorly-inferiorly can cause ring fractures of the base of the skull running in the middle fossae and through the squama of the temporal and occipital bone, expulsion of the corpus ossis

occipitale or marginal fractures at the front side of the foramen magnum. The reasons for this are not completely known. Inter-individual differences in the strength of the bones and/or the soft tissues is a possible explanation. Hinz (1970) has emphasized the importance of changes due to degeneration in the localization of injuries to the cervical spine. The exact position of the victim's head in relation to his trunk at the moment of impact, which is also of importance, could not be determined precisely by the reconstructions.

The thorough investigation of the cervical spines and the close reconstructions of the course of events in the accidents in the present investigation not only suggest several fracture mechanisms not earlier mentioned in the literature available, but differ from the general opinions concerning the genesis of fractures of the atlas and axis.

It is earlier known that ring fractures of the base of the skull running in the floor of the middle fossae and through the squama of the temporal and occipital bone can be due to: traction-retroflexion of the head-neck, traction-anteroflexion of the head-neck, impression of the vertebral column into the interior of the skull (LeCount and Hockzema, 1934; Moritz, 1954; Patscheider, 1961; Voigt, 1962).

The present investigation (I), however, shows several further mechanisms:

1. Torsion in the base of the skull by a trauma obliquely from in front against the temple or obliquely from behind against the posterior part of the side of the head.
2. Retroflexion of the head due to an impact from behind against the occiput below the center of gravity of the head.
3. Wedge effect due to trauma against the forehead.
4. Anteroflexion of the head due to a blow from above and behind against the posterior part of the vertex of the head.

Further findings, not earlier reported, are that an exceptionally strong blow against the victim's face from in front can under special circumstances cause expulsion of the entire body of the occipital bone together with the surroundings of the foramen magnum due to shearing effect, and that a trauma from below and from in front against the face can also cause expulsion of the corpus ossis occipitale or marginal fracture at the front side of the foramen magnum.

The most notable finding concerning the genesis of atlas fractures (II, VI) is that in no case did the fractures seem to be due entirely to the universally-accepted wedge-effect after impact against the head, so-called classical Jefferson's fracture (Jefferson, 1920, 1927; Ruge, 1969; Braakman et al, 1971; Shapiro et al, 1973; Sherk, 1975; Barker et al, 1976). Instead, two mechanisms not earlier suggested were observed.

1. Axial compression of the neck most pronounced anteriorly and laterally causing the anterior margin of one superior joint surface of the axis to split off the anterior arch of the atlas. The result of the experimental study may indicate that in these cases the anterior (separated) border of the foramen magnum can force the anterior arch of the atlas inferiorly.

2. Axial compression of the neck combined with oblique retroflexion of the head resulting in dislocation and tilting in posterior-inferior direction of one lateral mass of the atlas.

The findings suggest that the classical Jefferson's fracture is rarer than usually thought.

The findings furthermore indicate that - contrary to general opinion (von Torklus et al, 1970; Stewart et al, 1977) - avulsion fractures of the inferior margin of the anterior arch are due to lateral tilting of the head and are not very rare lesions.

The general opinion that fractures of the posterior arch can be due to retroflexion of the head (Jefferson, 1920; von Torklus et al, 1970; Shapiro et al, 1973) is supported by the results of the present investigation which, however, also emphasize that simultaneously occurring fractures of the odontoid process of the axis is a contributing factor. Concerning atlas fractures due to trauma to the chin from in front and below, our findings support the occasionally-stated opinion (Schmitt et al, 1977) that traction of the neck most pronounced on either the right or left side causes considerable strains and stresses in the atlas.

As to axis fractures (III, IV, VI) the most notable observation is that bilateral fractures of the neural arch in the region of the isthmus (hangman's fracture) often are the result of anteroflexion of the head. This mechanism is mentioned only occasionally in the literature

(DeLorme, 1967; Maurice-Williams, 1973; Balau et al, 1974); Termansen, 1974; Taylor et al, 1976) while retroflexion is the fracture mechanism almost universally accepted (Schneider et al, 1965; Ruge, 1969; Portnoy et al, 1971; Elliott et al, 1972; Brashear et al, 1975; Marar, 1975; Sherk, 1975; Williams, 1975; Seljeskog et al, 1976). Furthermore, simultaneous traction or compression of the neck seem to be of importance in the genesis of these fractures.

Another observation which is not mentioned in the literature available is that notably non-symmetrical fractures of the neural arch indicate oblique anteroflexion of the head. However, according to the result of one of the impact experiments, it cannot be excluded that bilateral differences in the tolerance of the neck tissues can be of importance, i.e. that notably non-symmetrical, bilateral fractures of the neural arch of the axis can also result from straight anteroflexion of the head. It has been said that hangman's fracture occurring in traffic accidents usually arises through mechanisms not identical with the one in judicial hanging, and furthermore that accident victims sustaining this type of fracture usually exhibit none or only slight injuries to the cord (Braakman et al, 1971; Elliott et al, 1972; Husby, 1974; Termansen, 1974; Brashear et al, 1975; Sherk, 1975; Williams, 1975; Seljeskog et al, 1976). However, in most of the accident victims in the present investigation the fracture arose in the same way as did the fracture in the case of hanging (IV) (anteroflexion of the head in combination with traction of the neck) and in several of these cases the cord was disrupted. The concept that hangman's fracture is a "benign" lesion is based on clinical materials, i.e. on the fortunate accident victims in which the traction at the moment of the accident was not great enough to sufficiently lacerate the soft tissues surrounding the fracture and allow a disruption of the cord to take place.

Regarding fractures of the odontoid process the results support the opinion that they can be due to retroflexion and anteroflexion of the head (Blockey et al, 1956; Hipp et al, 1963; Böhler, 1971; Shapiro et al, 1973) and that simultaneous rotation of the head may be a contributing factor (Blockey et al, 1956; Hipp et al, 1963) but the results do not support the opinion that only shearing effect in the horizontal plane can cause such fractures (Ruge, 1969; Portnoy et al, 1971). Furthermore, in regard

to odontoid process fractures the findings indicate that force in the longitudinal plane must be taken into account, a factor which has not been stressed in the available literature. Thus, simultaneous compression of the neck seems to be of importance when the fractures result from anteroflexion or retroflexion of the head due to a trauma against the upper part of the head. On the other hand, lack of simultaneous traction in the neck probably helps restrict a possible axis fracture to the odontoid process when the head anteroflexes after impact against the lower part of the face or against the anterior side of the neck. The importance of a remaining cartilaginous disc within the axis in the genesis of fractures of the odontoid process is contested (Blockey et al, 1956). The findings in the present investigation suggest that a remaining disc may be of importance in the shape of the fracture.

The findings in two cases sustaining sagittal fractures of the cervical vertebral bodies (V) indicate that contrary to the fracture mechanisms earlier suggested (chiseling-action by means of the body of a neighbouring vertebra (Blumensaat, 1948, 1953), hypomochlion-action by means of a nucleus pulposus (Stimpfl, 1949)) pressure against the posterior part of a cervical vertebra can cause such a deformation of the vertebral ring that a sagittal fracture of its body results.

In a few cases in the present material both a skull base ring fracture and a fracture of the odontoid process or neural arch of the axis were present. von Torklus (1970) and Daum et al (1977) have published cases with simultaneous occurrences of fractures of the odontoid process and neural arch of the axis. It is questionable if the two fractures in the same case have been caused by only one impact or if two different impacts are responsible for the injuries. If both fractures are due to traumatization with the same direction against the same area of the head or neck it is most reasonable to suppose that they arose at the same time, i.e. by the same trauma and not by two impacts because a second trauma against the same area can be expected to cause further soft tissue lacerations around the first-arisen fracture and not a second fracture in some other location within the base of the skull or the atlas-axis. If, however,

a second trauma impacts another area of the head or neck and has another direction it is possible that a second fracture can result.

Based on the results of the present investigation it may be possible to perform purposeful investigations concerning the mean tolerance of the base of the skull and the cervical spine against the above-mentioned impacts. Evaluation of mean tolerance levels is necessary in order to take protective measures, for example in designing safe automobiles, helmets for motorcyclists etc. However, it is probably difficult to perform experimental investigations concerning the tolerance against head and neck fractures. Human volunteers cannot, of course, be subjected to impacts of sufficient magnitude. The value of animal experiments is reduced by anatomical dissimilarities and that of cadaver experiments by post mortem changes in the tissues and lack of muscular tone. One way seems to be to use mathematical models based on detailed studies of the tolerance of different tissues.

Presently, therefore, protective measures against the reported head and neck injuries must to a great extent be based on studies of accident victims.

The fractures of the base of the skull, the atlas, and axis studied in this investigation are often found in car occupants sustaining accidents. Although, it is generally considered that the use of seat belts offers good protection to car occupants, it has been claimed that in head-on collisions the use of seat belts especially increases the risk of spinal injuries (Büttner et al, 1960; Hamilton, 1968; Kurock et al, 1972; Rogers, 1974). Therefore, one part of this investigation (VII) has been focused on the spine of belt-wearing car occupants killed in head-on collisions. The results show that the above-mentioned fears are exaggerated if three-point belts are used. On the contrary, the results strongly emphasize the adequate protection against injuries to the base of the skull and the upper part of the neck that these belts afford. They reduce the risk of submarining and of violent impact of the occupant's head against the car interior which often causes severe head and neck injuries.

Another important observation is the increased risk of spinal injuries in the cervical and the thoraco-lumbar region caused by impact of not-belted back-seat passengers against the back of front-seat occupants in head-on collisions. This risk has been pointed out also by Dalgaard et al (1973) and demonstrates the importance of the use of belts by back-seat occupants too.

The findings also confirm the general opinion, that the use of shoulder-belts (possibility of submarining) or lap-belts only (anteroflexion of the upper part of the body) does not offer sufficient protection in head-on collision.

It is worth emphasizing that there is no case in the present material in which the victim sustained severe neck injuries due to a whip-lash mechanism because of a rear-end collision. In one case of this type the back of the driver's seat was bent backwards, the driver was thrown to the back-seat and the posterior part of her head impacted against the lower frame of the rear window, resulting in severe injuries to her cervical spine. This case demonstrates that the occasionally-stated opinion (States et al, 1970) that a backward bending of the back of the front seats during a rear-end collision protects the neck of the occupants is not valid. The latter opinion has been put forward also by Aldman (1972) and Dalgaard et al (1973).

CONCLUDING REMARKS

The opinion that fractures of the cervical spine - especially of its upper part - are not seldom overlooked both in clinical and post mortem investigations is supported by the findings in this investigation. The external injuries can be very slight and hemorrhages in the external and medial muscle layers of the posterior part of the neck and in the soft tissues anterior to the cervical spine can be very small or even lacking. Therefore, in the practical forensic-medical work, it is of great importance that the cervical spine - especially its upper part - is carefully investigated in all cases showing external injuries - also small ones - to the head. This includes not only those cases in which the circumstances indicate traumatic fatality but also cases of unexpected death in which the cause of death is not obvious.

The discovery of fractures in the upper part of the cervical spine combined with spinal cord injury in cases of unexpected death usually results in insurance and other judicial consequences. By using the investigation method proposed in this paper the risk of overlooking fatal injuries in the upper part of the neck is considerably reduced.

The correlation between ring fractures of the base of the skull, the atlas fractures and/or the axis fractures on the one hand and the site and direction of the impact against the head-neck on the other which has been established in this investigation has important applications in several areas:

1. Clinically, i.e. in predicting the type of injury to be suspected after trauma against the head-neck.
2. Prophylactically, i.e. in car design to reduce the risk of these injuries.
3. Legally, i.e. in the reconstruction of the course of events in complicated cases.

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